

The kinetic dark-mixing in the light of CoGENT and XENON100

Yann Mambrini^{a*}

^a *Laboratoire de Physique Théorique*
Université Paris-Sud, F-91405 Orsay, France

Several string or GUT constructions motivate the existence of a *dark* $U(1)_D$ gauge boson which interacts with the Standard Model only through its kinetic mixing. We compute the dark matter abundance in such scenario and the constraints in the light of the recent data from CoGENT, CDM-SII and XENON100. We show in particular that a region with relatively light WIMPS, $M_{Z_D} \lesssim 40$ GeV and a kinetic mixing $10^{-4} \lesssim \delta \lesssim 10^{-3}$ is not yet excluded by the last experimental data and seems to give promising signals in a near future. We also compute the value of the kinetic mixing needed to explain the DAMA/CoGENT/CRESST excesses and find that for $M_{Z_D} \lesssim 30$ GeV, $\delta \sim 10^{-3}$ is sufficient to fit with the data.

I. INTRODUCTION

Neutral gauge sectors with an additional dark $U(1)_D$ symmetry in addition to the Standard Model (SM) hypercharge $U(1)_Y$ and an associated Z_D are among the best motivated extensions of the SM, and give the possibility that a dark matter candidate lies within this new gauge sector of the theory. Extra gauge symmetries are predicted in most Grand Unified Theories (GUTs) and appear systematically in string constructions. Larger groups than $SU(5)$ or $SO(10)$, like E_6 allows the SM gauge group to be embedded into them. Brane-world $U(1)$'s are special compared to GUT $U(1)$'s because there is no reason for the SM particle to be charged under them. For a review of the phenomenology of the extra $U(1)$'s generated in such scenarios see e.g. [1]. On the other hand, recent anomalies in cosmic rays and direct detection experiments have motivated the exploration of new gauge interactions in a putative dark sector [2–5]. The new vector boson Z_D can interact with the SM, even if no SM fermions are directly charged under the additional gauge symmetry. This interaction occurs via mixed kinetic terms between the SM's hypercharge field strength and the new abelian field strength [6–12]. Very recently, a possibility of effective higgs couplings to the dark sector generated through a triangular loop of Z and/or Z_D has been analyzed in [13] and string scenarios can lead to naturally light hidden photons [14]. Other important consequences and clear dark matter signatures in satellite telescopes are studied in [15–17]

Our objective is triple: to know if, taking into account the last data and analysis from CDM-SII, CoGENT and XENON100, there is still part of the parameter space allowed by all constraints, especially WMAP and the electroweak precision tests. Secondly, considering CoGENT, CDM-SII or DAMA as *signal* events, we compute the kinetic mixing and Z_D mass required to fit the excesses. Finally, if we consider that the last XENON100 results exclude CoGENT and DAMA excesses, we project the fu-

ture sensitivity needed to explore the remaining part of the parameter space. The paper is organized as follows: after an introduction to the model and its motivations, we look in details the cosmological and accelerator constraints we should apply for our study. We then look at the parameter space already reached out by XENON100 and CDM-Si and fit the last data released by CoGENT, DAMA and CRESST. We conclude with some prospects for the XENON100 experiment.

II. THE MODEL

The matter content of any *dark* $U(1)_D$ extension of the SM can be decomposed into three families of particles:

- The *Visible sector* is made of particles which are charged under the SM gauge group $SU(3) \times SU(2) \times U(1)_Y$ but not charged under $U(1)_D$ (hence the *dark* denomination for this gauge group)
- the *Dark sector* is composed by the particles charged under $U(1)_D$ but neutral with respect of the SM gauge symmetries. The dark matter (ψ_0) candidate is the lightest particle of the *dark sector*
- The *Hybrid sector* contains states with SM and $U(1)_D$ quantum numbers. These states are fundamental because they act as a portal between the two previous sector through the kinetic mixing they induce at loop order.

From these considerations, it is easy to build the effective lagrangian generated at one loop :

$$\begin{aligned} \mathcal{L} = & \mathcal{L}_{\text{SM}} - \frac{1}{4} \tilde{B}_{\mu\nu} \tilde{B}^{\mu\nu} - \frac{1}{4} \tilde{X}_{\mu\nu} \tilde{X}^{\mu\nu} - \frac{\delta}{2} \tilde{B}_{\mu\nu} \tilde{X}^{\mu\nu} \\ & + i \sum_i \psi_i \gamma^\mu D_\mu \psi_i + i \sum_j \Psi_j \gamma^\mu D_\mu \Psi_j \end{aligned} \quad (1)$$

B_μ being the gauge field for the hypercharge, X_μ the gauge field of $U(1)_D$ and ψ_i the particles from the hidden

* Yann.Mambrini@th.u-psud.fr

sector, Ψ_j the particles from the hybrid sector, $D_\mu = \partial_\mu - i(q_Y \tilde{g}_Y \tilde{B}_\mu + q_D \tilde{g}_D \tilde{X}_\mu + g T^a W_\mu^a)$, T^a being the $SU(2)$ generators, and

$$\delta = \frac{\tilde{g}_Y \tilde{g}_D}{16\pi^2} \sum_j q_Y^j q_D^j \log \left(\frac{m_j^2}{M_j^2} \right) \quad (2)$$

with m_j and M_j being hybrid mass states [18].

Notice that the sum is on all the hybrid states, as they are the only ones which can contribute to the $Y_\mu X_\mu$ propagator. After diagonalization of the current eigenstates that makes the gauge kinetic terms of Eq.1 diagonal and canonical, we can write after the $SU(2)_L \times U(1)_Y$ breaking¹:

$$\begin{aligned} A_\mu &= \sin \theta_W W_\mu^3 + \cos \theta_W B_\mu \\ Z_\mu &= \cos \phi (\cos \theta_W W_\mu^3 - \sin \theta_W B_\mu) - \sin \phi X_\mu \\ (Z_D)_\mu &= \sin \phi (\cos \theta_W W_\mu^3 - \sin \theta_W B_\mu) + \cos \phi X_\mu \end{aligned} \quad (3)$$

with, at the first order in δ :

$$\begin{aligned} \cos \phi &= \frac{\alpha}{\sqrt{\alpha^2 + 4\delta^2 \sin^2 \theta_W}} \quad \sin \phi = \frac{2\delta \sin \theta_W}{\sqrt{\alpha^2 + 4\delta^2 \sin^2 \theta_W}} \\ \alpha &= 1 - M_{Z_D}^2/M_Z^2 - \delta^2 \sin^2 \theta_W \\ &\pm \sqrt{1 - M_{Z_D}^2/M_Z^2 + 4\delta^2 \sin^2 \theta_W} \end{aligned} \quad (4)$$

and $+$ ($-$) sign if $M_{Z_D} < (>) M_Z$. The kinetic mixing parameter δ generates an effective coupling of SM states ψ_{SM} to Z_D , and a coupling of ψ_0 to the SM Z boson which induces an interaction on nucleons. Developing the covariant derivative on SM and ψ_0 fermions state, we computed the effective $\psi_{\text{SM}} \psi_{\text{SM}} Z_D$ and $\psi_0 \psi_0 Z$ couplings at first order in δ . One can find other implications of such construction in [18–20]

III. THE CONSTRAINTS

A. The cosmological constraint

The abundance of a thermal relic dark matter candidate ψ_0 is controlled by its annihilation cross section into

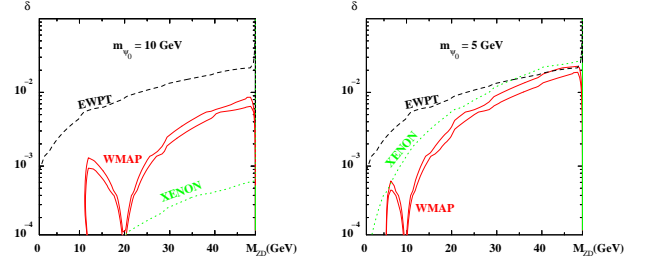


FIG. 1. Two examples of allowed parameter space for $m_{\psi_0} = 10$ GeV (left) and $m_{\psi_0} = 5$ GeV (right). The points between the full-red region respect the 5σ WMAP constraint, the points below the dashed-black line do not exceed accelerator data on precision tests, and the points above the dotted-green line are excluded by XENON100 data.

SM particles mediated by the exchange of a Z_D gauge boson through s -channel or t -channel $Z_D Z_D$ final state (see [15, 16] for a detailed study of the relic abundance constraints). We modified the micrOMEGAs2.2.CPC code² [22] in order to calculate the relic abundance of ψ_0 . We show in Fig.1 the points that fulfill the WMAP 5σ bound [23] on Ω_{DM} for $m_{\psi_0} = 10$ GeV (left) and 5 GeV (right) in the (M_{Z_D}, δ) plane. One can clearly see the Z_D -pole region when $M_{Z_D} \sim m_{\psi_0}$. One important point is that for a given M_{Z_D} and m_{ψ_0} , there exists a unique solution δ (up to the very small uncertainties at 5σ) fulfilling WMAP constraints: from 3 parameters $(m_{\psi_0}, M_{Z_D}, \delta)$, the WMAP constraints reduce it to two (M_{Z_D}, δ) .

B. The electroweak precision constraints

Concerning the electroweak symmetry breaking, the mixing between \tilde{X}_μ and \tilde{B}_μ generates new contributions to precision electroweak observables. However, none of the particle of the SM has any $U(1)_D$ charges: the $U(1)_D$ can be considered has a *lepto-hadrophobic* Z_D . Other authors in [5, 24, 25] or [26] have looked at hidden-valley like models or milli-charged dark matter but concentrating their study to relatively heavy Z_D and large mixing angle. The authors of [21] have computed the observables from effective Peskin-Takeuchi parameters[27], and found

$$\begin{aligned} \Delta m_W &= (17\text{MeV}) \zeta \\ \Delta \Gamma_{l+l-} &= -(8\text{keV}) \zeta \\ \Delta \sin^2 \theta_W^{eff} &= -(0.00033) \zeta \end{aligned} \quad (5)$$

¹ Our notation for the gauge fields are $(\tilde{B}^\mu, \tilde{X}^\mu)$ before the diagonalization, (B^μ, X^μ) after diagonalization and (Z^μ, Z_D^μ) after the electroweak breaking.

² The author wants to thank particularly G. Belanger and S. Pukhov for their help to address this issue.

where

$$\zeta \equiv \left(\frac{\delta}{0.1}\right)^2 \left(\frac{250\text{GeV}}{m_X}\right)^2 \quad (6)$$

Different electroweak measurements from LEP give $|\zeta| \lesssim 1$. These constraints are represented by the black line in Fig.1. A new analysis was made more recently in [28] and [29] but they confirmed that in models with extra $U(1)$'s which does not couple at tree-level with SM particles (like a leptophobic Z_D for instance) or with the higgses, the constraints on the mass of the gauge boson are very weak. The only case where one can put some strongest constraints is if a non-trivial higgs sector acts as a portal between the Dark sector and the SM one at tree level (like in Supersymmetry for instance).

However, for the mass range of interest in this work ($m_{Z_D} \sim 10$ GeV) we needed to look at the search of production/decay of hidden bosons at low energy $e+e-$ colliders [27]. Indeed, over a large range of parameters, the cross sections for the production of dark-sector particles scale as

$$\sigma \sim \frac{gg_D \delta^2}{16\pi^2 E_{cm}^2} \quad (7)$$

where E_{cm} is the center-of-mass energy of the collider. The search sensitivity of a given e^+e^- machine above mass threshold scales as the ratio of integrated luminosity over squared center-of-mass energy, $\mathcal{L}_{int}/E_{cm}^2$. LEP and Tevatron are much less sensitive to direct production of low mass dark sectors than the B-factories.

While writing the present article, the authors of [32] have published an extensive model independent analysis in the energy range of interest in our study. They bounded the kinetic mixing by $\delta \lesssim 0.03$ for $10 \text{ GeV} < M_{Z_D} < 200 \text{ GeV}$ which is in complete agreement with the constraints given by Eq.5 plotted in Fig.1. Their strongest upper limit ($\delta \lesssim 0.03$) come from a *wide* Z_D whose dark decay is maximized. For $M_{Z_D} \lesssim 10 \text{ GeV}$, they also computed a model dependent exclusion from BaBar searches and obtained $\delta \lesssim 3 \times 10^{-3}$ which is also in agreement with Eqs.5.

C. The XENON/ CDMS constraints

In recent months, there have been new data releases from many experiments that have engendered a great deal of excitement (see section IV B for a discussion and references). The XENON100 collaboration has recently released new dark matter limits [33], placing particular emphasis on their impact on searches known to be sensitive to light-mass (~ 10 GeV) WIMPs. The existing

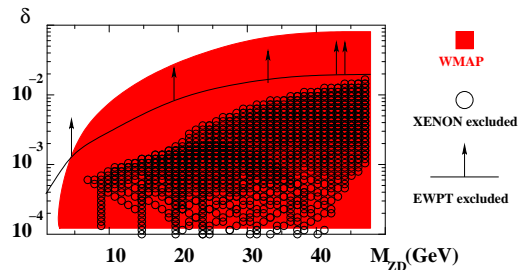


FIG. 2. Constraints coming from WMAP (red boxes), electroweak data (black line), and recent direct detection analysis of XENON100 after correction of their efficiency factor [33]

bounds set by the XENON10 [34], and the recognition that the effect of channeling in NaI(Tl) crystal is less important than previously assumed [35] can be combined by the full data set released recently by CDMS [36] to obtain tighter bounds to the elastic cross section. In our work, we will use the analysis made by the authors of [37], whereas a similar analysis can be found in [38]. In practice, the differences between CDMS and XENON constraints appear when $m_{\psi_0} \lesssim 10 \text{ GeV}$, where CDMS-Si is more sensitive than XENON100 [up to the renormalization used for the calculation of the XENON100 efficiency discussed in the section IV B]. We show in Fig.1 two examples of points, one excluded (left) and the other one allowed (right) by XENON100.

IV. RESULTS

A. Combining all the constraints

We show in Fig.2 the parameter space still allowed after applying all the constraints described above. The red points respect WMAP constraints after a scan on m_{ψ_0} , and the ones below the black lines are not excluded by electroweak precision tests. The points with black circle are excluded by the last data released by the XENON experiment. We observe that a region with $M_{Z_D} \lesssim 40 \text{ GeV}$ and $10^{-4} \lesssim \delta \lesssim 10^{-3}$ is still open. We can understand easily why for increasing values of the kinetic mixing the XENON constraints seem to weaken: for a fixed M_{Z_D} , higher values of δ increase the annihilation cross section, and decrease the relic density. To fulfill WMAP, one needs to find a point with m_{ψ_0} far away from the pole ($M_{Z_D}/2$), and therefore lighter. This is a region that XENON has difficulties to exclude: the sensitivity of a direct detection experiments decreases for light dark matter candidate as their efficiencies are worst for low-energy nuclear recoil. For instance, for $M_{Z_D} = 20.6 \text{ GeV}$ and $\delta_1 = 10^{-4}$, WMAP is fulfilled for $m_{\psi_0} = 10.5 \text{ GeV}$, which is a point lying exactly in the Z_D -pole region. The spin independent elastic scattering on the pro-

ton is in this case $\sigma_{SI}^p = 7 \times 10^{-40} \text{ cm}^2$ which is already excluded by XENON and CDMS-Si. However, for $\delta_2 = 4 \times 10^{-3}$, WMAP is fulfilled for $m_{\psi_0} = 4.04 \text{ GeV}$, quite away from the Z_D pole, generating a higher cross section $\sigma_{SI}^p = 10^{-38} \text{ cm}^2$ ($\delta_2 > \delta_1$) but which is not yet excluded by XENON whose sensitivity is $3.5 \times 10^{-38} \text{ cm}^2$ for such a light ψ_0 .

B. Signals from COGENT, CRESST or DAMA?

The DAMA collaboration has provided strong evidence for an annually modulated signal in the scintillation light from sodium iodine detectors. The combined data from DAMA/NaI [39] (7 annual cycles) and DAMA/LIBRA [40] (4 annual cycles) with a total exposure of 0.82 ton yrs shows a modulation signal with 8.2σ significance. The phase of this modulation agrees with the assumption that the signal is due to the scattering of a WIMP.

Recently, the CoGeNT collaboration has announced the observation of an excess of low energy events relative to expected background [41]. This excess, if interpreted as dark matter, implies the dark matter particles possess a mass in the range of 5-15 GeV and an elastic scattering cross section with nucleons of the order of 10^{-4} pb . Moreover, recently, a series of analysis and comments have been released concerning the effective value of the XENON100 efficiency at low energy (L_{eff}). We will not enter into all the technical details here, a complete analysis of the computation of L_{eff} and its consequence on the constraints that we can derive from the XENON experiment can be found in [42–46]. The main conclusion (until now) is that it is not yet clear if the DAMA/LIBRA and CoGeNT regions are excluded by XENON100 (see [48] for a model independent analysis concerning light dark matter scenario). The main discussion concerns the extrapolation of L_{eff} and its interpretation in the detection of $S1$ light from low-energy nuclear recoil. To be as conservative as possible, we explore in this section the possibility to interpret these excesses with a dark sector with a kinetic mixing portal.

We show in Fig.3 the points respecting WMAP, and the DAMA/LIBRA (with and without channeling) CoGeNT and CRESST³ results at 90 % of CL. In performing our fits, we have used the 13 DAMA/LIBRA bins below 8.5 keVee and the 28 CoGeNT bins between 0.4 and 1.8 keVee. The data at higher energies will not include any events from dark matter particles in the mass range considered here, and the inclusion of higher energy bins would not affect our results in any significant way. Concerning the CRESST result, it is important to emphasize that some fraction of the events observed in

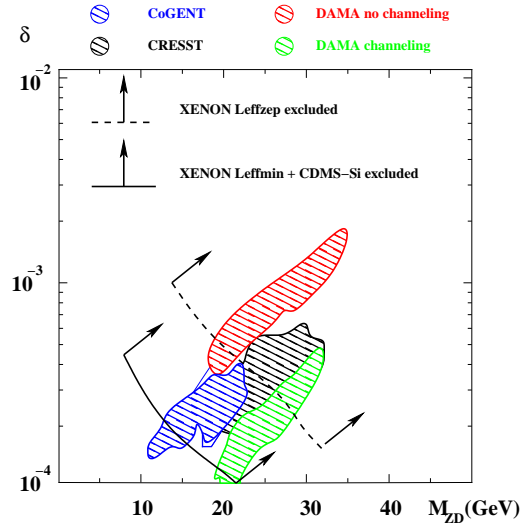


FIG. 3. Parameter space allowed within 90 % of C.L. for the CoGeNT signal (blue), DAMA without channeling (red), with channeling (green), CRESST (black), and the exclusion region depending on the hypothesis concerning L_{eff} (see the text for details).

the oxygen band could be spillage from CRESST’s alpha or tungsten bands, neutron backgrounds, or be the result of radioactive backgrounds. Further information from the CRESST collaboration will be essential for understanding these results. All the constraints have been calculated for a standard Maxwellian velocity distribution (with mean velocity $v_0 = 230 \text{ km/s}$ and an escape velocity $v_{esc} = 600 \text{ km/s}$). One can observe in Fig.3 that for all experiments, the regions are quite surprisingly near and correspond to $10 \text{ GeV} \lesssim M_{Z_D} \lesssim 30 \text{ GeV}$ and $10^{-4} \lesssim \delta \lesssim 10^{-3}$, which is in complete agreement with the measurement of electroweak precision tests. Moreover, such values of δ are typical of one loop-order corrections and can easily be generated by heavy-fermions loops in the $Z - Z_D$ propagator.

We show in Fig.4 the points respecting the accelerator, cosmological, and the more severe direct detection constraints in the plane $(m_{\psi_0}; \sigma_{SI}^p)$ in comparison with XENON100 and CDMS-Si sensitivity. To take into account the uncertainties on L_{eff} , we plotted 3 exclusion limit for XENON corresponding to the best fit set by XENON100 in [33], which give $L_{eff} \simeq 0.12$ (L_{effMed}) at small nuclear recoil energy E_{nr} . A more conservative choice (L_{effMin} , corresponding to a lower 90 % C.L. fit to the data) gives a L_{eff} which decreases monotonically with E_{nr} and vanishes at $E_{nr} < 1 \text{ keV}$. The ZEPLIN experiment (also a Xe experiment) uses a different L_{eff} , which is essentially zero below 6-7 keV (L_{effZep} here). For dark matter masses below $\sim 10 \text{ GeV}$, the CDMS-II silicon detectors provide very stringent constraints [49] due to the favorable kinematics of the lighter target nucleus. However, the observed CDMS-II silicon nuclear recoil quenching is not reproduced by Linhard theory [50].

³ For the CRESST estimation, we used an extrapolation given in the talk of T. Schwetz and the CRESST collaboration [47].

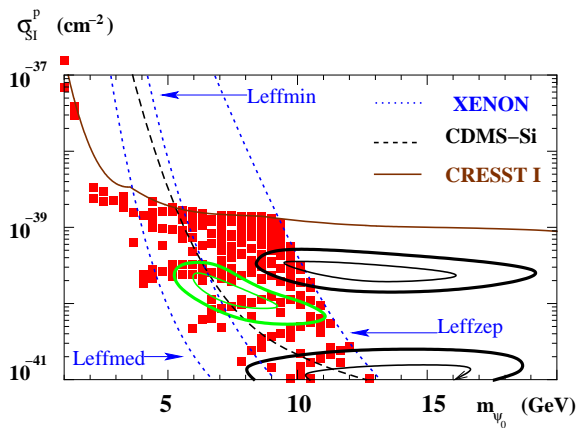


FIG. 4. Points still allowed by electroweak, cosmological and direct detection constraints in the plane $(M_{\psi_0}; \sigma_{SI}^p)$. The green region corresponds to CoGeNT (minimum χ^2 , with contours at 90 and 99.9% C.L.), assuming a constant background contamination [41]. The DAMA regions (goodness-of-fit, also at 90 and 99.9 % C.L.) are given both with (upper black region) and without (lower black region) channelling [40]. The black dashed line is the 90 % C.L. exclusion limit for the CDMS-Si [36] and the brown full line the 90% C.L. exclusion limit for the CRESST I experiment [52]. The blue dotted lines corresponds to the 90% C.L. exclusion limit from the XENON100 experiment corresponding respectively to the LeffMed (left), Leffmin (middle) and LeffZep (right) scintillation efficiency -see text for details.

This discrepancy could indicate a $\sim 20 - 30$ % error in the low energy calibration [51]. The uncorrected exclusion curve is also presented in Fig.4. We also took into account the exclusion limit at 90% of C.L. from CRESST-I experiment with sapphire-based cryogenic detector at a threshold of 600 eV [52]. We see that a large region is still to be explored. It corresponds to dark matter masses between 1 and 10 GeV, a range of masses which could be difficult but far from impossible to probe in a near future experiment.

During the completion of this work, the authors of [51] showed that even without channeling but when taking into account uncertainties in the relevant quenching factors, a dark matter candidate with a mass of approxi-

mately ~ 7 GeV and a cross section with nucleons of $\sigma_p^{SI} \sim 2 \times 10^{-40} \text{ cm}^2$ could account for both these observations. Even if the values they used for the Na quenching factor can be considered extreme to some extent, these results correspond to a dark gauge boson mass $M_{Z_D} \sim 15$ GeV and $\delta \sim 2 \times 10^{-4}$, which is in the range of interest for our present study. Other interesting constraints to check would be the antimatter production/detection as computed in specific final states cases in [53], galactic gamma-ray or from the isotropic diffuse emission [54] and colliders perspectives [55].

V. CONCLUSION

We showed that the existence of a *dark* $U(1)_D$ gauge sector which interacts with the Standard Model only through its kinetic mixing possesses a valid dark matter candidate respecting accelerator, cosmological and the more recent direct detection constraints. Moreover, considering the latest results of DAMA/LIBRA, CoGENT and CRESST, we demonstrated that a specific range of the kinetic mixing ($\delta \sim 10^{-4} - 10^{-3}$) can explain all these excesses for a dark boson mass $M_{Z_D} \sim 10 - 20$ GeV. Such a value of kinetic mixing is intriguingly in agreement with the value one can expect if the mixing is generated by heavy hybrid-fermions loop corrections. Other models have similar specificities ([56] for instance) : the diagram for annihilation is the same than the one leading the scattering process (Z_D exchange in the former case, h exchange in the latter). We also showed that the region of the parameter space still allowed by all constraints will be difficult but far from impossible to probe in a near future.

ACKNOWLEDGEMENTS

Y.M. wants to thank particularly E. Dudas, T. Schwetz, G. Belanger, N. Fornengo and A. Romagnoni for useful discussions. The work was supported by the french ANR TAPDMS **ANR-09-JCJC-0146** and the spanish MICINN Consolider-Ingenio 2010 Programme under grant Multi- Dark **CSD2009-00064** and the E.C. Research Training Networks under contract **MRTN-CT-2006-035505**.

[1] P. Langacker, Rev. Mod. Phys. **81** (2008) 1199 [arXiv:0801.1345 [hep-ph]].
 [2] N. Arkani-Hamed, D. P. Finkbeiner, T. R. Slatyer and N. Weiner, Phys. Rev. D **79** (2009) 015014 [arXiv:0810.0713 [hep-ph]].
 [3] M. Pospelov and A. Ritz, Phys. Lett. B **671** (2009) 391 [arXiv:0810.1502 [hep-ph]].
 [4] S. Baek and P. Ko, JCAP **0910** (2009) 011 [arXiv:0811.1646 [hep-ph]].

[5] Z. Liu, Nucl. Phys. Proc. Suppl. **200-202** (2010) 133 [arXiv:0910.0061 [hep-ph]].
 [6] B. Holdom, Phys. Lett. B **166**, 196 (1986).
 [7] K. R. Dienes, C. F. Kolda and J. March-Russell, Nucl. Phys. B **492** (1997) 104 [arXiv:hep-ph/9610479].
 [8] S. P. Martin, Phys. Rev. D **54** (1996) 2340 [arXiv:hep-ph/9602349].
 [9] T. G. Rizzo, Phys. Rev. D **59** (1999) 015020 [arXiv:hep-ph/9806397].

- [10] F. del Aguila, M. Masip and M. Perez-Victoria, Nucl. Phys. B **456** (1995) 531 [arXiv:hep-ph/9507455].
- [11] B. A. Dobrescu, Phys. Rev. Lett. **94** (2005) 151802 [arXiv:hep-ph/0411004].
- [12] T. Cohen, D. J. Phalen, A. Pierce and K. M. Zurek, arXiv:1005.1655 [hep-ph].
- [13] K. Cheung, K. H. Tsao and T. C. Yuan, arXiv:1003.4611 [hep-ph].
- [14] M. Goodsell, J. Jaeckel, J. Redondo and A. Ringwald, JHEP **0911** (2009) 027 [arXiv:0909.0515 [hep-ph]]; S. A. Abel, M. D. Goodsell, J. Jaeckel, V. V. Khoze and A. Ringwald, JHEP **0807** (2008) 124 [arXiv:0803.1449 [hep-ph]].
- [15] Y. Mambrini, JCAP **0912**, 005 (2009) [arXiv:0907.2918 [hep-ph]];
- [16] E. Dudas, Y. Mambrini, S. Pokorski and A. Romagnoni, JHEP **0908**, 014 (2009) [arXiv:0904.1745 [hep-ph]];
- [17] C. B. Jackson, G. Servant, G. Shaughnessy, T. M. P. Tait and M. Taoso, JCAP **1004**, 004 (2010) [arXiv:0912.0004 [hep-ph]].
- [18] M. Baumgart, C. Cheung, J. T. Ruderman, L. T. Wang and I. Yavin, JHEP **0904** (2009) 014 [arXiv:0901.0283 [hep-ph]].
- [19] M. Pospelov, A. Ritz and M. B. Voloshin, Phys. Lett. B **662** (2008) 53 [arXiv:0711.4866 [hep-ph]].
- [20] M. Pospelov, Phys. Rev. D **80** (2009) 095002 [arXiv:0811.1030 [hep-ph]]; M. Pospelov, A. Ritz and M. B. Voloshin, Phys. Lett. B **662** (2008) 53 [arXiv:0711.4866 [hep-ph]].
- [21] J. Kumar and J. D. Wells, Phys. Rev. D **74**, 115017 (2006) [arXiv:hep-ph/0606183].
- [22] G. Belanger, F. Boudjema, A. Pukhov and A. Semenov, arXiv:1005.4133 [hep-ph]; G. Belanger, F. Boudjema, A. Pukhov and A. Semenov, Comput. Phys. Commun. **180**, 747 (2009) [arXiv:0803.2360 [hep-ph]]; G. Belanger, F. Boudjema, A. Pukhov and A. Semenov, Comput. Phys. Commun. **177**, 894 (2007).
- [23] D. N. Spergel *et al.* [WMAP Collaboration], Astrophys. J. Suppl. **170** (2007) 377 [arXiv:astro-ph/0603449]; E. Komatsu *et al.* [WMAP Collaboration], arXiv:0803.0547 [astro-ph].
- [24] D. Feldman, Z. Liu and P. Nath, Phys. Rev. D **75** (2007) 115001 [arXiv:hep-ph/0702123].
- [25] W. F. Chang, J. N. Ng and J. M. S. Wu, Phys. Rev. D **74** (2006) 095005 [Erratum-ibid. D **79** (2009) 039902] [arXiv:hep-ph/0608068].
- [26] S. Cassel, D. M. Ghilencea and G. G. Ross, Nucl. Phys. B **827** (2010) 256 [arXiv:0903.1118 [hep-ph]].
- [27] K. S. Babu, C. F. Kolda and J. March-Russell, Phys. Lett. B **408**, 261 (1997) [hep-ph/9705414]; B. Batell, M. Pospelov and A. Ritz, Phys. Rev. D **80** (2009) 095024 [arXiv:0906.5614 [hep-ph]]; B. Batell, M. Pospelov and A. Ritz, Phys. Rev. D **79** (2009) 115008 [arXiv:0903.0363 [hep-ph]].
- [28] J. Erler, P. Langacker, S. Munir and E. Rojas, AIP Conf. Proc. **1200**, 790 (2010) [arXiv:0910.0269 [hep-ph]].
- [29] F. del Aguila, J. de Blas and M. Perez-Victoria, arXiv:1005.3998 [hep-ph].
- [30] J. D. Bjorken, R. Essig, P. Schuster and N. Toro, Phys. Rev. D **80**, 075018 (2009) [arXiv:0906.0580 [hep-ph]]; R. Essig, P. Schuster and N. Toro, Phys. Rev. D **80**, 015003 (2009) [arXiv:0903.3941 [hep-ph]]; R. Essig, P. Schuster, N. Toro and B. Wojtsekhowski, arXiv:1001.2557 [hep-ph].
- [31] A. Aranda and C. D. Carone, Phys. Lett. B **443**, 352 (1998) [arXiv:hep-ph/9809522].
- [32] A. Hook, E. Izaguirre and J. G. Wacker, arXiv:1006.0973 [hep-ph].
- [33] E. Aprile *et al.* [XENON100 Collaboration], arXiv:1005.0380 [astro-ph.CO].
- [34] J. Angle *et al.* [XENON10 Collaboration], Phys. Rev. D **80** (2009) 115005 [arXiv:0910.3698 [astro-ph.CO]].
- [35] Z. Ahmed *et al.* [The CDMS-II Collaboration], arXiv:0912.3592 [astro-ph.CO].
- [36] Z. Ahmed *et al.* [CDMS II collaboration], Science **327** (2010) 1619.
- [37] J. Kopp, T. Schwetz and J. Zupan, JCAP **1002** (2010) 014 [arXiv:0912.4264 [hep-ph]].
- [38] S. Chang, J. Liu, A. Pierce, N. Weiner and I. Yavin, arXiv:1004.0697 [hep-ph].
- [39] R. Bernabei *et al.*, Riv. Nuovo Cim. **26N1** (2003) 1 [arXiv:astro-ph/0307403].
- [40] R. Bernabei *et al.* [DAMA Collaboration], Eur. Phys. J. C **56** (2008) 333 [arXiv:0804.2741 [astro-ph]].
- [41] C. E. Aalseth *et al.* [CoGeNT collaboration], arXiv:1002.4703 [astro-ph.CO].
- [42] J. I. Collar and D. N. McKinsey, arXiv:1005.0838 [astro-ph.CO].
- [43] T. X. Collaboration, arXiv:1005.2615 [astro-ph.CO].
- [44] J. I. Collar and D. N. McKinsey, arXiv:1005.3723 [astro-ph.CO].
- [45] C. Savage, G. Gelmini, P. Gondolo and K. Freese, arXiv:1006.0972 [astro-ph.CO].
- [46] J. I. Collar, arXiv:1006.2031 [astro-ph.CO].
- [47] see talk by W. Seidel, WONDER 2010 Workshop, Laboratory Nazionali del Gran Sasso, Italy, March 22-23, 2010 and MPIK seminar by T. Schwetz, June 21, 2010.
- [48] A. L. Fitzpatrick, D. Hooper and K. M. Zurek, Phys. Rev. D **81** (2010) 115005 [arXiv:1003.0014 [hep-ph]].
- [49] J. Filippini [CDMS Collaboration], Les Rencontres de Physique de la Vallée d'Aoste, *Nuovo Cimento C* **32** 05-06 (2009).
- [50] G. Gerbier, E. Lesquoy, J. Rich *et al.*, Phys. Rev. **D42**, (9):3211-3214 (1990); B. L. Dougherty, Phys. Rev. **A45**, (3):2104-2107 (1992).
- [51] D. Hooper, J. I. Collar, J. Hall and D. McKinsey, arXiv:1007.1005 [hep-ph].
- [52] G. Angloher *et al.*, Astropart. Phys. **18** (2002) 43;
- [53] J. Lavalle, arXiv:1007.5253 [astro-ph.HE].
- [54] C. Arina and M. H. G. Tytgat, arXiv:1007.2765 [astro-ph.CO]; V. Barger, Y. Gao, M. McCaskey and G. Shaughnessy, arXiv:1008.1796 [hep-ph].
- [55] J. Goodman, M. Ibe, A. Rajaraman, W. Shepherd, T. M. P. Tait and H. B. P. Yu, arXiv:1008.1783 [hep-ph].
- [56] S. Andreas, C. Arina, T. Hambye, F. S. Ling and M. H. G. Tytgat, arXiv:1003.2595 [hep-ph]; S. Andreas, T. Hambye and M. H. G. Tytgat, JCAP **0810** (2008) 034 [arXiv:0808.0255 [hep-ph]].